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IFERC-CSC

Development of Monte-Carlo Scheme for Runaway Electron Generation and Confinement Code

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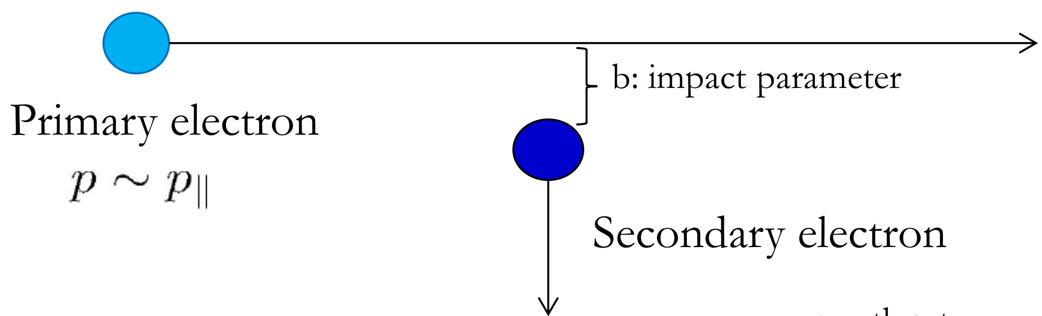
Runaway Electron is a big issue in ITER …

Background

- Runawaly Electrons generated during disruption may cause substantial damage to plasma facing components. In ITER, significant runaway generation is predicted theoretically, for which avalanche amplification plays an essential role.

Avalanche amplification due to close collisions

(Rosenbluth & Putvinski, 1997)



Current Amplification Rate

$$\gamma \tau_{\rm CQ} \sim \frac{I_p}{I_A \ln \Lambda}$$

γ: growth rate

τ_{CQ}: current quench time

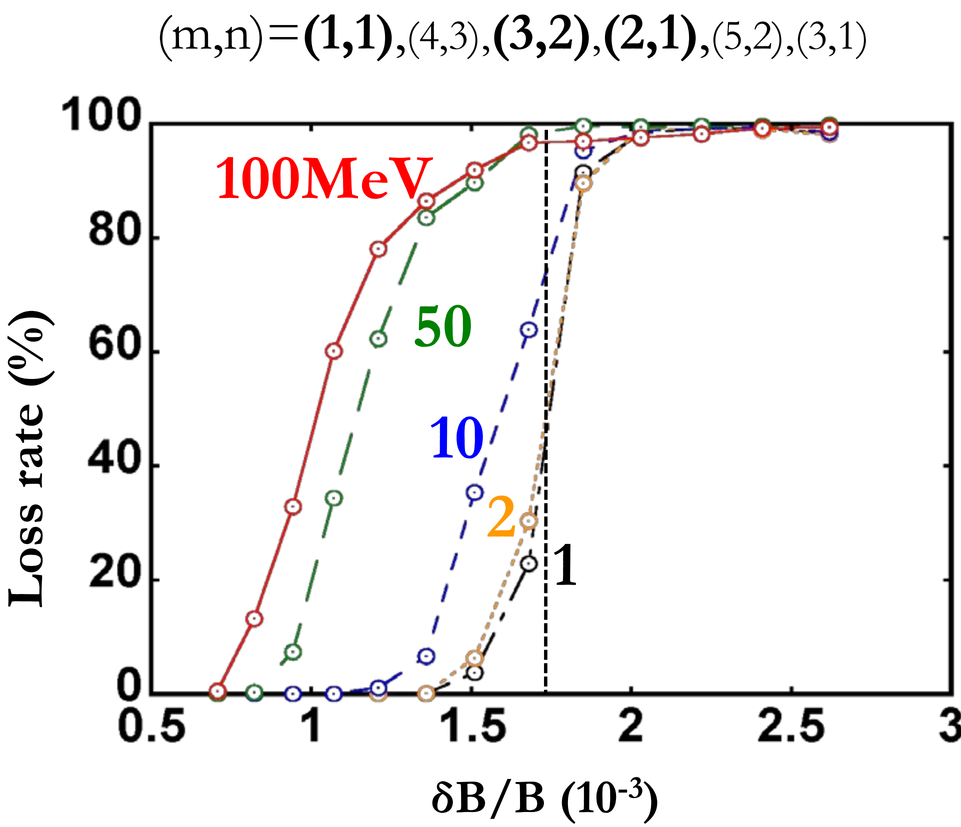
I_p: plasma current

I_A: Alfvén current

ETC-Rel code

Background

- Collisionless orbit simulation ETC-Rel has been developed in JAEA (Tokuda 1999-; Matsuyama, et al., 2012-)



- Orbit loss rate in presence of low-order magnetic perturbation has been studied previously (Matsuyama, et al., submitted to JPSJ suppl.)
- This work extends ETC-Rel to include runaway generation mechanisms with self-consistent electric field model.

New version of ETC-Rel

A simulation model

- Self-consistent runaway source and electric field model is newly implemented in ETC-Rel.

(1) Orbit Push

↓

(2) Collision

↓

(3) Solve Electric Field (Surface averaging approx.)

↓

(4) Introduce particle source

f = f(electric field, runaway density)

Orbit push

A simulation model

- Original version of ETC-Rel code solves collisionless orbit of runaway electrons for given energy and pitch angle with the relativistic guiding-center equations.

- Guiding-center equations
(Cary & Brizard, 200)

$$\frac{d\mathbf{X}}{dt} = \frac{p_\parallel}{m\gamma}\frac{\mathbf{B}^{**}}{B_\parallel^{**}} + \mathbf{E}^* \times \frac{\mathbf{b}}{B_\parallel^{**}}$$

$$\frac{dp_\parallel}{dt} = e\frac{\mathbf{B}^{**}}{B_\parallel^{**}} \cdot \mathbf{E}^*$$

$$\mathbf{E}^* = \mathbf{E} - \frac{\mu}{e}\nabla B - \frac{p_\parallel}{e}\frac{\partial \mathbf{b}}{\partial t}$$

$$\mathbf{B}^* = \mathbf{B} + \frac{p_\parallel}{e}\nabla \times \mathbf{b}$$

$$\mathbf{B}^{**} = \mathbf{B}^* + \delta\mathbf{B} \qquad \delta\mathbf{B} = \nabla \times (\alpha\mathbf{B})$$

- Interface to MEUDAS equilibrium code for realistic tokamak geometry
- MPI-OpenMP hybrid code (tested 32-128 node in Helios)
- Solving GC eqs. in Cylindrical coordinates including the vacuum region.
- Possible to take into account magnetic perturbations into the calculation.

Relativistic Collisions

A simulation model

- Monte-Carlo Collision Operator [G. Papp, et al., (2011)]

(1) Pitch angle scattering

$$\frac{d}{dt}\xi = -\mathcal{I}(q)\xi \qquad \frac{d}{dt}\sigma_\xi^2 = \mathcal{I}(q)(1-\xi^2)$$

(2) Slowing-down and energy scattering

$$\frac{d}{dt}q = \frac{1}{\tau q^2}\left\{-\mathcal{J}(q)(1+q^2) + \frac{\partial}{\partial q}[\mathcal{J}(q)\mathcal{P}(q)]\right\} \qquad \frac{d}{dt}\sigma_q^2 = \frac{2}{\tau q^2}\mathcal{J}(q)\mathcal{P}(q)$$

$$\mathcal{J}(q) = \frac{q^2}{\epsilon(1+q^2)}G\left(\frac{q}{\sqrt{2\epsilon(1+q^2)}}\right) \qquad \epsilon = v_t^2$$

$$\mathcal{P}(q) = \frac{\epsilon\sqrt{1+q^2}^3}{q}$$

$$\mathcal{I}(q) = \frac{\sqrt{1+q^2}}{\tau q^3}\left[Z_{\text{eff}} + \Phi\left(\frac{q}{\sqrt{2\epsilon(1+q^2)}}\right) - G\left(\frac{q}{\sqrt{2\epsilon(1+q^2)}}\right) + \epsilon\frac{q^2}{1+q^2}\right]$$

Generation Source Model

A simulation model

- Source model

Primary electron generation (Dreicer acceleration, Connor & Hastie NF)

$$\dot{n}_r^I \simeq \frac{n_e}{\tau}\left(\frac{m_e c^2}{2T_e}\right)^{3/2}\left(\frac{E_D}{E_\parallel}\right)^{3(1+Z_{\rm eff})/16}\exp\left(-\frac{E_D}{4E_\parallel}-\sqrt{\frac{(1+Z_{\rm eff})E_D}{E_\parallel}}\right)$$

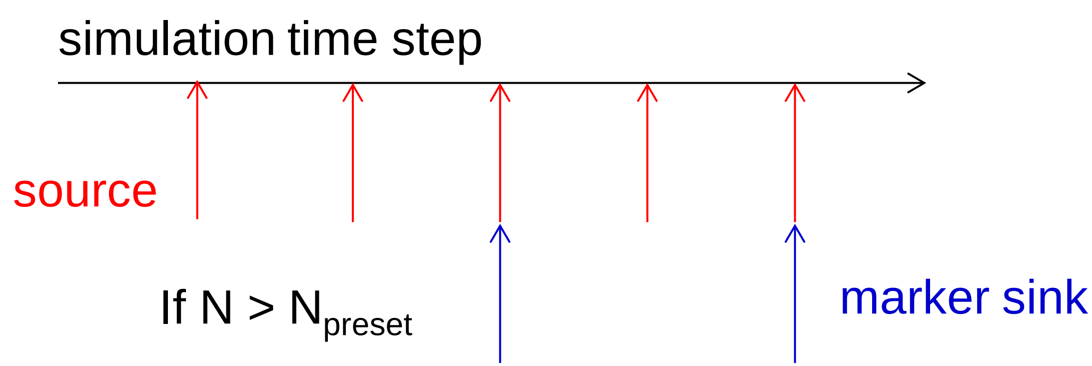
Secondary electron generation (Avalanche amplification, Rosenbluth & Putvinski NF)

$$\dot{n}_r^{II} \simeq n_r \frac{E_\parallel/E_c - 1}{\tau \ln L}\sqrt{\frac{\pi\varphi}{3(Z_{\rm eff}+5)}}\left(1-\frac{E_c}{E_\parallel}+\frac{4\pi(Z_{\rm eff}+1)^2}{3\varphi(Z_{\rm eff}+5)(E_\parallel^2/E_c^2+4/\varphi^2-1)}\right)^{-1/2}$$

Dreicer field $\quad E_D = \dfrac{m_e^2 c^3}{e\tau T_e}$

Critical field $\quad E_c = \dfrac{m_e c}{e\tau}$

Collision times $\quad \tau = \dfrac{4\pi\epsilon_0^2 m_e^2 c^3}{n_e e^4 \ln\Lambda}$



To keep total number of marker particles …

1D Electric Field Solver

A simulation model

- 1D model for solving parallel electric field

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_{\|}}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t}\left(\sigma_{\|} E_{\|} + j_{\mathrm{r}}\right)$$

  - Space: Finite Difference (Staggered mesh)
  - Time: Fully Implicit/Crank-Nicholson Scheme

- **Consider response of the runaway current to temperature drop**

$$T_e(t,r) = T_{\mathrm{final}}(r) + [T_0(r) - T_{\mathrm{final}}(r)]e^{-t/t_0}$$

- Runaway density and current are evaluated from ETC-Rel code with surface averaging (**full-f approach**).

$$n_r(\rho_i) = \frac{1}{\Delta V}\sum_i w_s^i, \quad w_s = N_p/N_s, \quad N_p \equiv \int d\rho\, n_r(\rho)\frac{dV}{d\rho}$$

Time history of Runaway Current

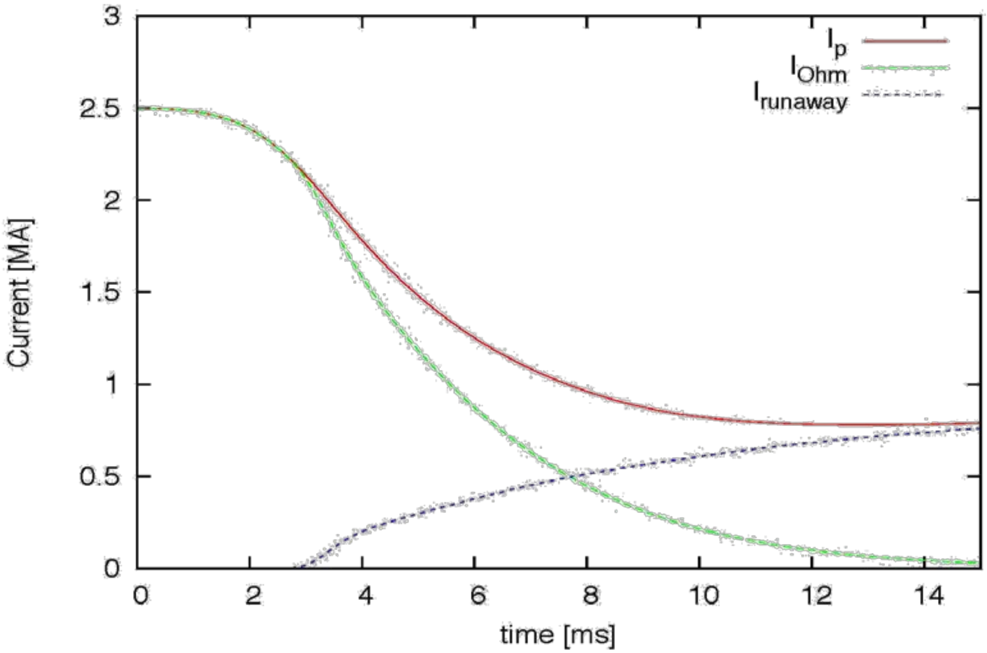
Simulation Results

- **First simulation has been carried out for a JT-60U size plasma**

  - elliptic cross section

  - R = 3.4 m, B = 3 T, a = 1 m, $\varkappa$ = 1.6, I_p = 2.5 MA

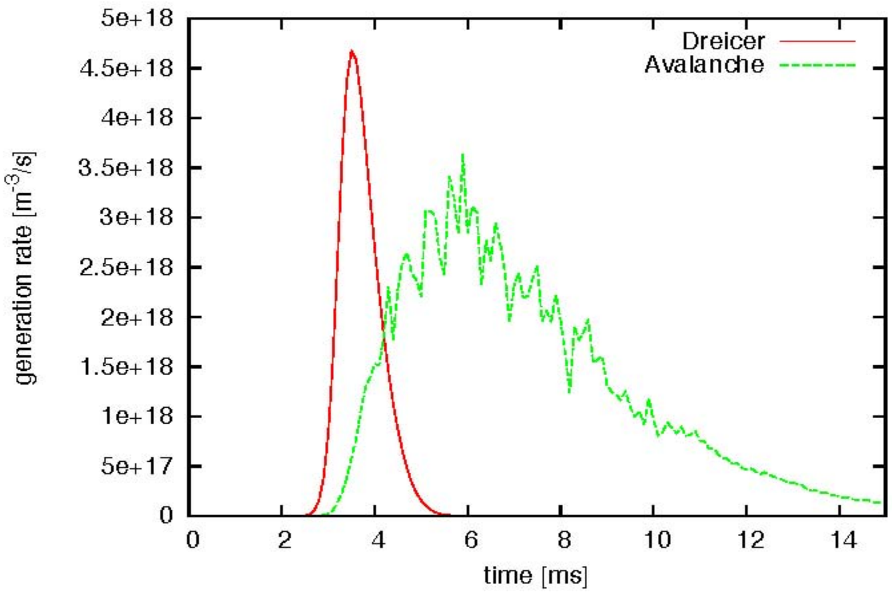
  - assuming thermal quench such that Te = 2 keV → 10 eV with constant electron density of 3×10^{19} m^{-3}.

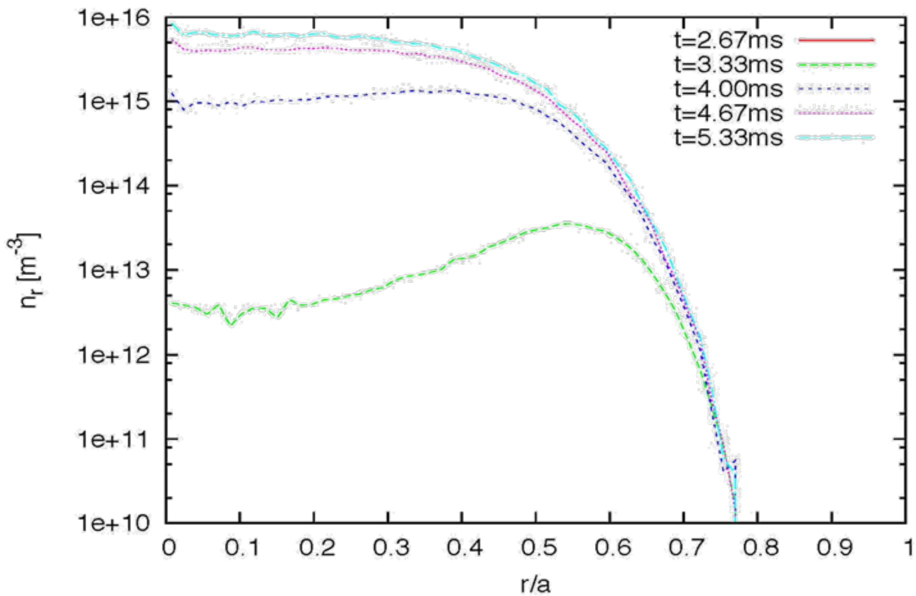


- **Current quench ~ 10 ms**
- **Runaway current ~ 750 kA**
- **Agree well with prediction by a cylindrical modeling (Smith, et al., PoP, 2006).**

Runaway Density Profiles

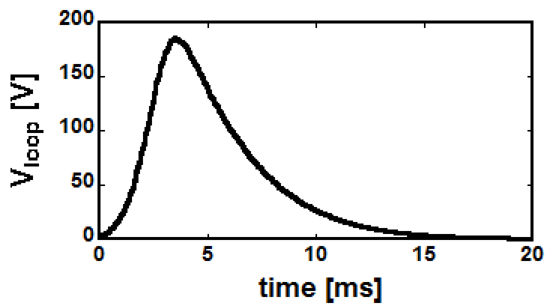
Simulation Results

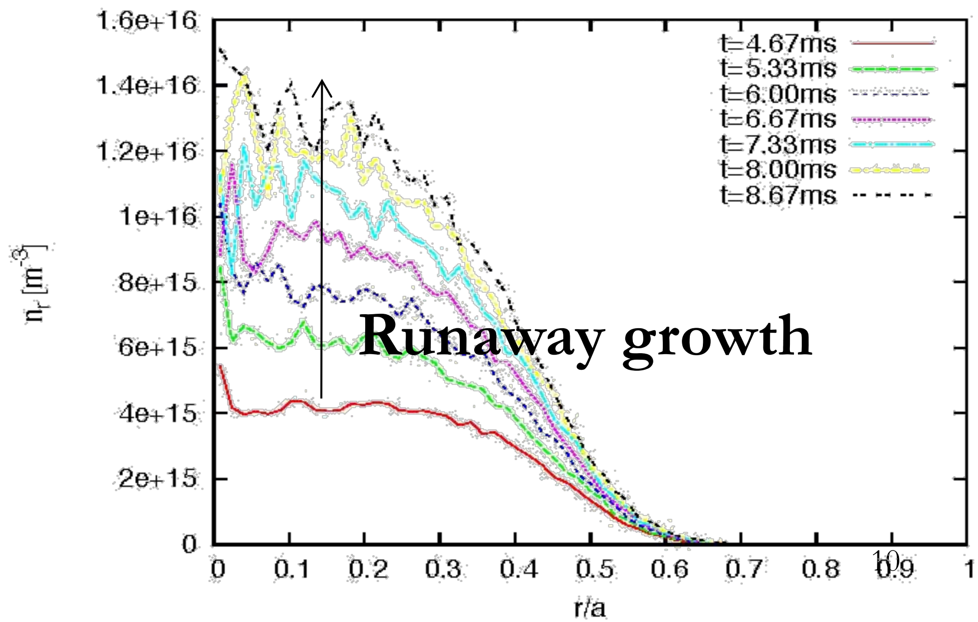




- Dreicer generation is significant only in early phase of disruption.

T<5ms: Dreicer generation
T>5ms: Avalanche



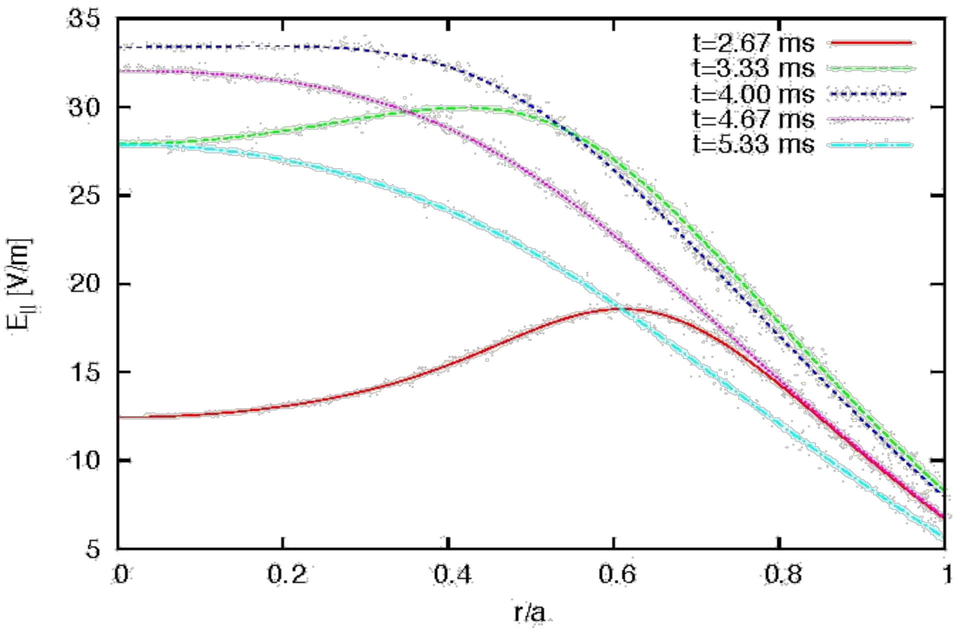


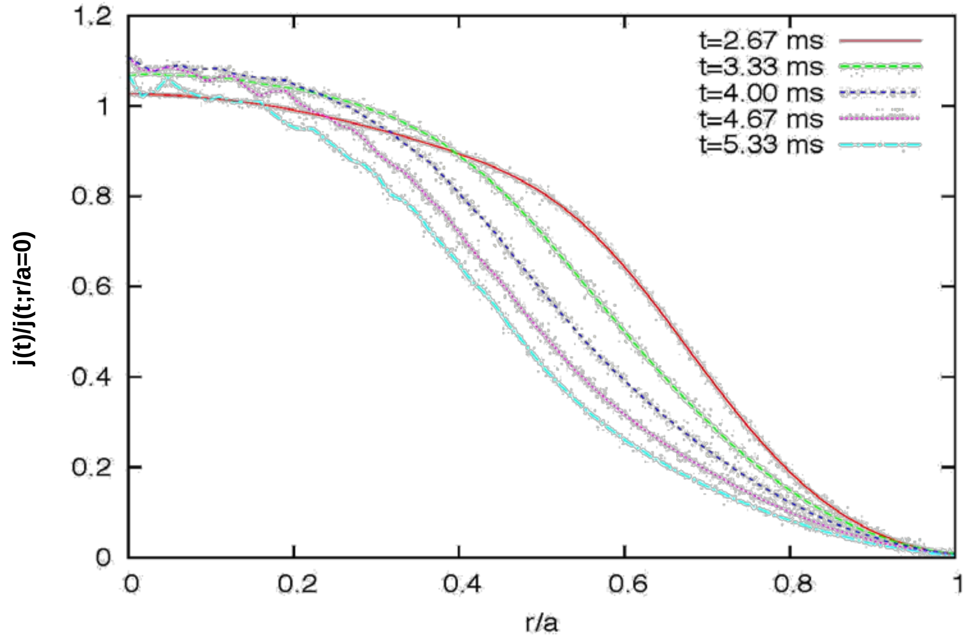
Current Profile Peaking with Runaways

Simulation Results

- **Electric field and current profiles**
  - Current profile peaking is consistent with Eriksson PRL 2004.
  - Electric field threshold: $E_c \sim 10^{-2}$ V/m, $E_d \sim 10^{3}$ V/m.

Only hot tail of electrons becomes runaways: $E_c << E_{||} << E_d$





Summary

Summary and Future Plan

- A new version of ETC-Rel has been developed, including runaway generation mechanisms and self-consistent electric field.
- In present version, **instead of directly solving the Dreicer acceleration, generation processes are included by analytical expressions of the runaway source** to save the computational time. First simulation results for JT-60U grade disruption have been presented.
- In future, **effects of low-order magnetic perturbation (such as n = 1) will be investigated, which cannot treat by conventional bounce-averaging approach because of their 3-D nature**.
- **Integration with 3-D MHD codes is currently being planned.**